Flexible AC Transmission Systems (FACTS) Devices
Dr. Avik Bhattacharya
Department of Electrical Engineering
Indian Institute of Technology Roorkee

Lecture – 30
Voltage and Phase Angle Regulator Device - II

Thank you for your kind attention. We shall continue our discussions with the FACTS Devices. This is will be a second lectures on the voltage and the phase angle regulator devices where we have left, we start from that point that is actually that tap changer is feeding highly inductive load, so this is the recapitulation of our previous class.

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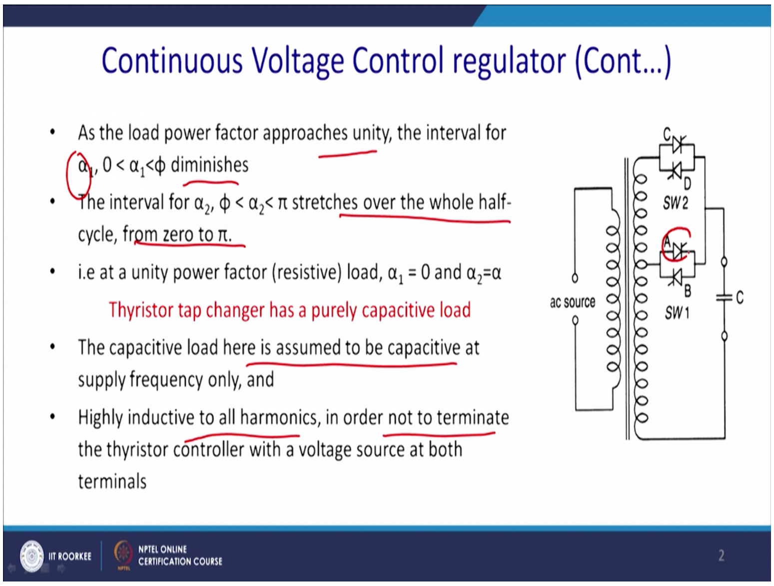

As the load power factor approaches unity, so that is for the resistive load that interval for in case of the inductive load you know, it is approaching to the resistive load, alpha should be form actually from actually change from 0 to phi, and it is diminishes. And the interval for alpha 2 will be actually phi to actually till pi, and stretches over the whole half cycle, for the pre at 0 to pi so that is the actually the changes.

That mean what happened in for in resistive kind of power factor you know at unity power factor, the load alpha 1 should be equal to 0, and alpha 2 will be equal to actually alpha. So, that is the actually, then the inductive loads actually goes to the resistive load.

Now, let us take another option, if the load is purely capacitive, the thyristor tap changer has a purely capacitive loading, it is quite difficult to analyze, because you know that these capacitor is dangerous. Their required the DID deputation and all those things, but since there is a leakage inductance across it so there is a series in that you already inserted so you can use it.

Capacitor load here is assumed to be capacitor, and the supply frequency only. Please note that of course, the according to the frequency the system become omega l or omega C can be capacity 1 negative. Highly inductive for all the harmonics, in order to actually terminate the thyristor control with the voltage source of the both the terminal, this is the configuration. So, upper half cycle actually when so of the lower thyristor will be named as A same as the what we have done in case of the inductive one; and lower is B, and upper is C and low is D.

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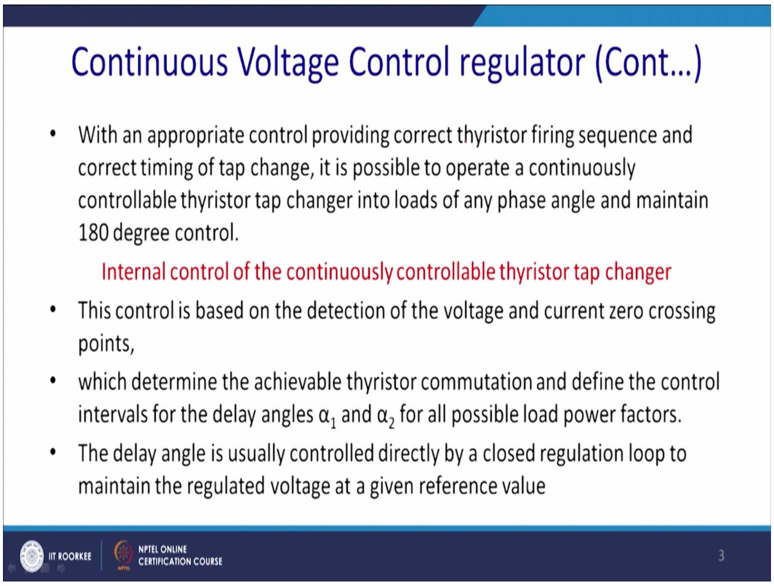

So, what happened, with an appropriate control providing the direct thyristor firing sequence, and correct timing tap change. This possible to operate a continuously controllable thyristor tap changer into the load to any phase angle, and you can maintain the 180 degree control. The internal control of this continuously control thyristors, will be discussed on.

This control is based on detections of the voltage, and the zero crossing point of the current, because here current will lead the voltage which determines the achievable thyristor commutations. And define the control interval for the delay angle alpha 1 and alpha 2 for all possible load factors. The delay angle is usually controlled directly by a close regulations loop to maintain the regulated voltage and a high reference value. So, this is the way actually it is being controlled.

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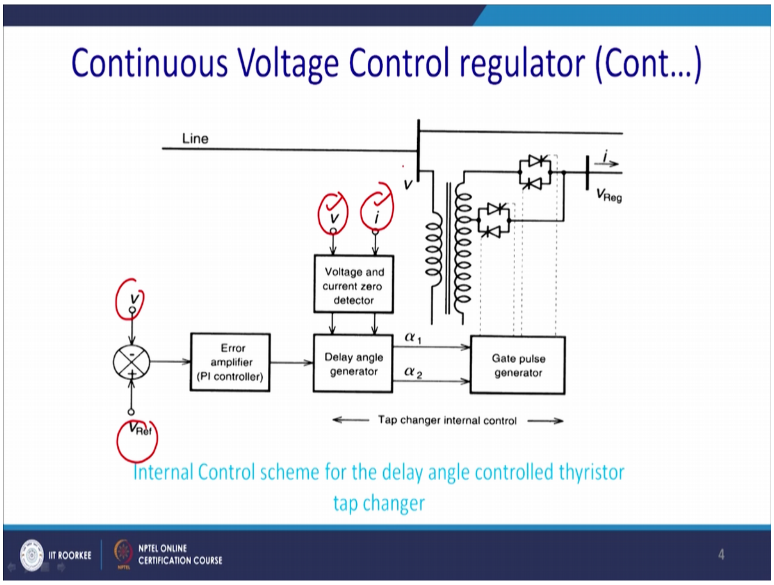

So, do you got a V and you got a V ref. See you got and P i controller from P i controller actually error can be calculated. And this is actually the information about the zero crossing of voltage and current. And they will be a delay angle estimation of alpha and alpha 2 an accordingly actually you change the thyristors according to the load. So, these information v 1 and v 2, v 1 and i 1 will depend on the type of load you will have.

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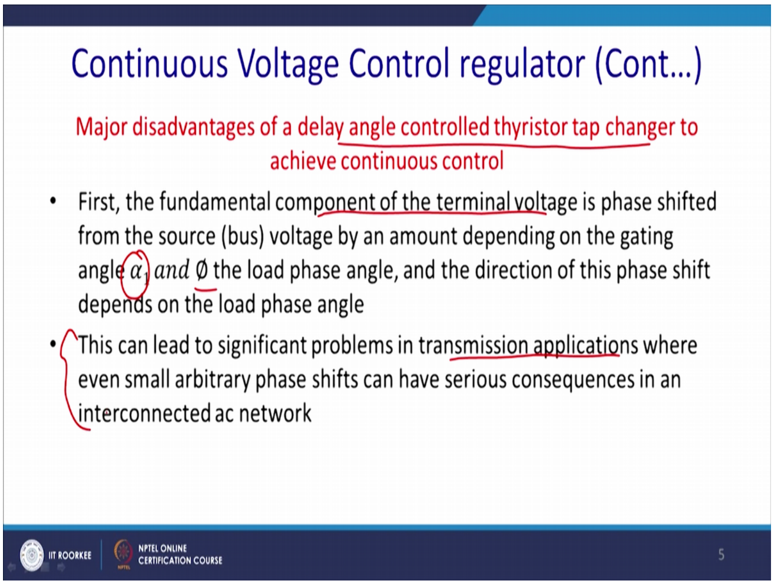

So, continuous voltage control regulation, major disadvantage of the delay angle control of the thyristor tap changer actually to harmonics, it injects harmonics. And for this we actually go towards thus continuous angle control method.

First, the fundamental component of the terminal voltage is phase shifted from the source voltage by amount depending on the getting angle alpha 1 and the phi, the load phase angle. And the direction of the phase shift depends on the load phase angle, whether it is inductive or capacitive, it depends on it. This can lead to significant problem in transmission line application, where small arbitrary phase shift can have a serious consequence in the interconnected network. So, you have we have discussed in our previous class, there is a circulating current. If there is a little phase angle delay, so it least to the phase angle delay, and thus we cannot do that.

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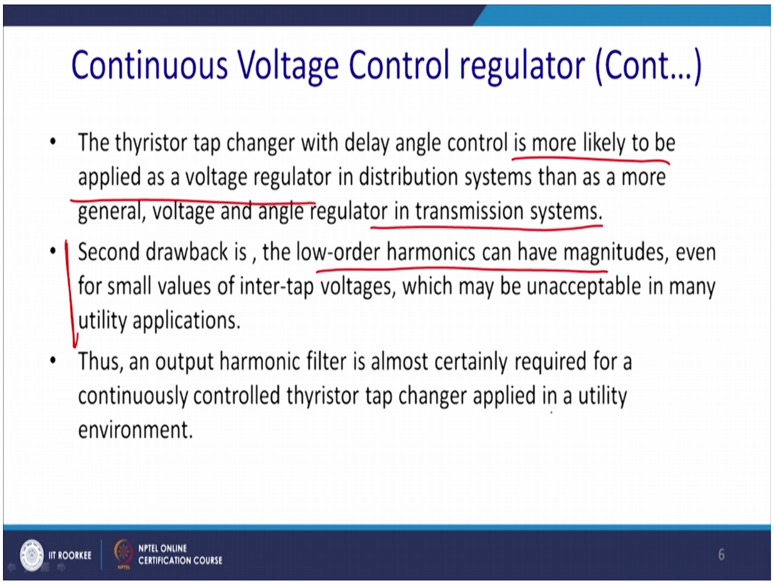

The thyristor tap changer with delay angle control is more likely to be applied as a voltage regulator in distribution system, than has a more general, voltage and the angular (Refer Time: 06:25) in transmission system. Second drawback is, the lower order harmonic actually have a quite sufficient magnitude, we have same the harmonic spectrum in our previous discussions. Low-order harmonic can have a magnitude, even small value of inter-tap voltages, which may be unacceptable in many utility applications.

So, for this results we have to actually get rid of this disturbance. Thus what happened to have to find the solution, and output harmonic filter is almost certainly required for continuously control thyristor tap changer applied to the utility environment that adds to the extra cost to the system.

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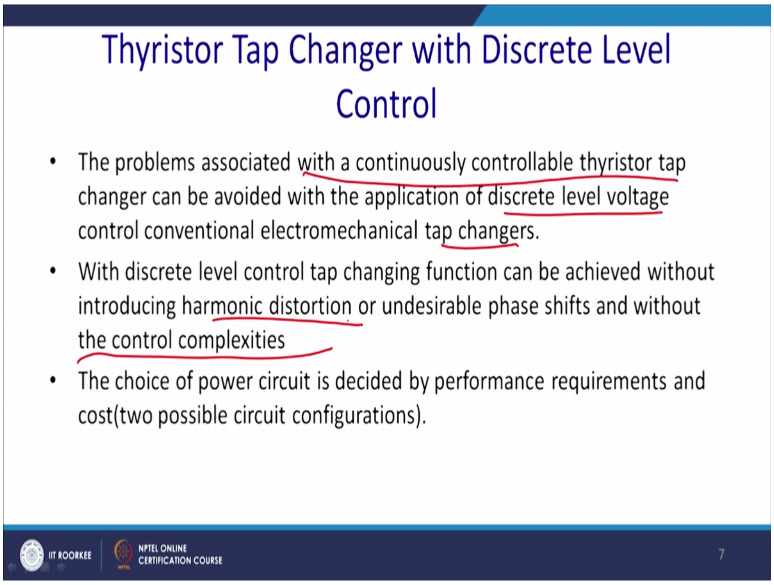

The problem associated with the continuously controlled thyristor tap changer can be avoided with the application of the discrete level voltage control conventional electromechanical tap changer that will see now.

With discrete level control tap changing function can be achieved without introducing harmonic distortion or undesirable phase shift without with any control complexities. So, it is just mechanical tap changer. So, it was previously connected to the n number of tons, thereafter it will be n 1 number of tons for n 1 is greater than in something like that. The choice of the power circuit is decided by performance requirement and the cost, two possible circuit configuration can be actually observed here.

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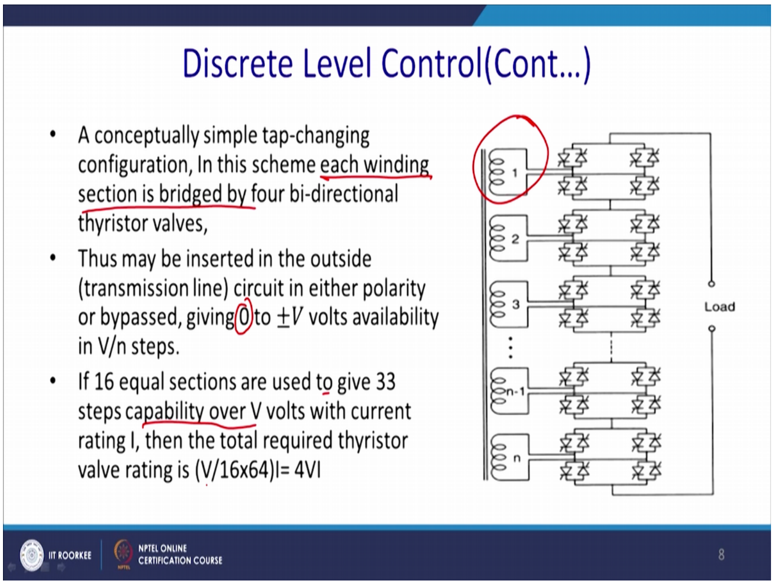

So, this is the case of discrete level voltage regulator. What happened, you can have a n number of actually secondary, and they have in cascaded. So, you have a, but you have a different level of it, and you can bypass a particular level, or you can take the level through the magnetics and thus you can step it or step it down. And in this case, either this actually 1 or 2 or any level is not used and thus actually turns ratio of primary to secondary get decreased or increase according to the requirement.

Conceptually, the simple tap changing configuration, in this scheme each winding section is bridged with four bi-directional thyristor valves. So, this is the four bi-directional thyristor valve. You can allow current to pass through this switches, pass through this magnetics, or you can simply bypass this magnetics, you have a choice.

Thus maybe inserted in the outside transmission line, the circuit either polarity or bypassed, noise] giving angle 0 or plus minus 0 volt to this V by n number of steps. If 16 equal sections are used, so that any 16 to give 33 capability over V volts, then thyristor will be consider below with the current rating i, then the total required thyristors will be actually thyristor rating is V by 16 into 64. So, that is actually quite high value of that is quite actually low voltage. So, that rating of the thyristors is practically available in our existing network.

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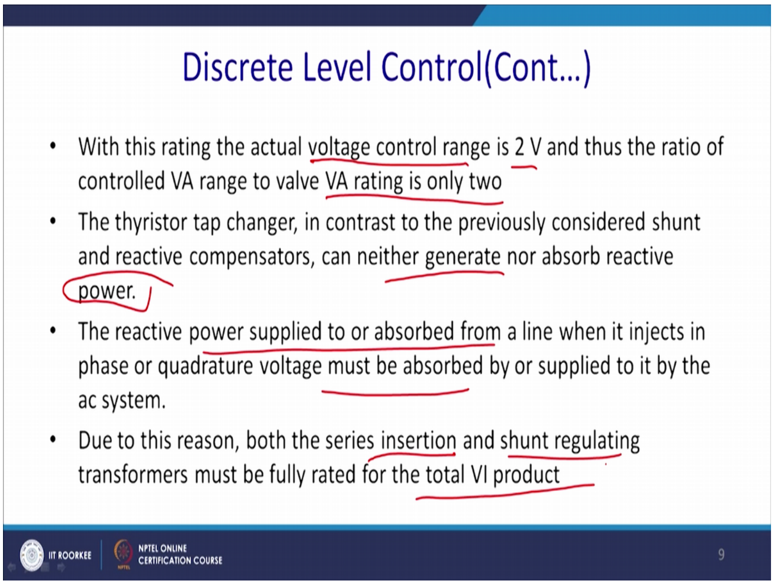

So, for this session this kind of modular kind of solution discrete level control is quite popular compare to that what we have discussed previously. The rating with this rating of the actual rating voltage control range is 2 V, and thus the ratio of the control VA range to the valve VA rating is only two. The thyristor tap changer, in contrast to the previously consider shunt or the reactive compensator, can either generate nor absorb reactive power. So, there cannot control the real power.

The reactive power supplied or absorbed form the line, where it injects in phase or quadrature voltage must be absorbed or supplied by the ac system or load. Due to this reason, both series in session insertion, and the shunt regulating transformer must fully rated to this actually the VI product of the rating. So, rating is quite high, in case of the both, shunt and the series solution.

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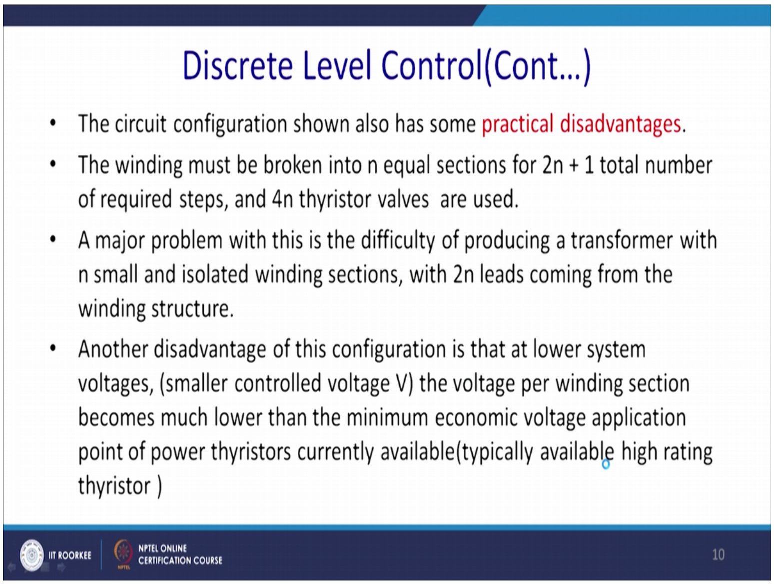

But here, this configuration has some practical disadvantage. The circuit configuration also has some practical disadvantages. The winding must be broken into n equal section for this kind of configurations required in steps, and 4n thyristors level as used as shown in the previous figure; The major problem with this difficulty of producing a transformer with n small and isolated winding section, with 2n leads coming from the winding structure. So, complexity is available with a manufacturing of such unique kind of transformer.

Another disadvantage of this configuration is that lower system voltage. Smaller controlled voltage V, the voltage per winding section becomes much lower, and the minimum economic voltage applications point of power thyristors available; Typically available power rating of the thyristors.

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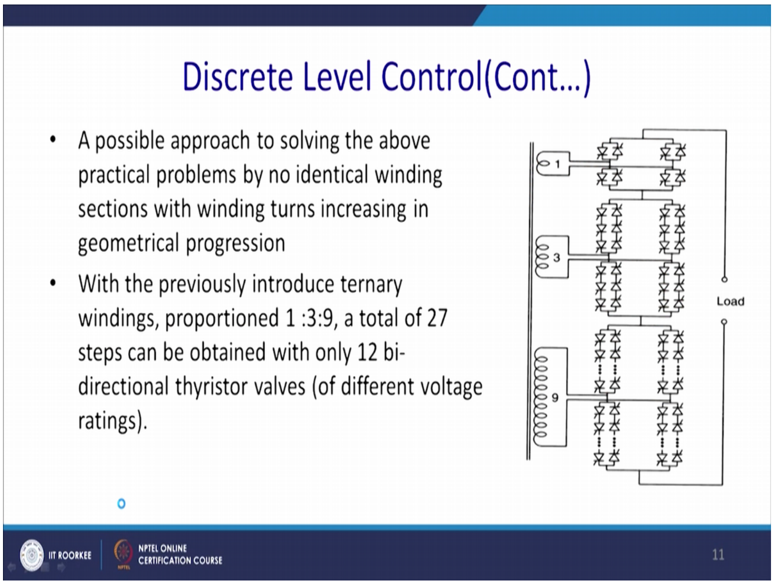

So, a possible approach to solve this problem, the above practical problem by no identical winding section with winding turns increasing in a geometrical progression that is what you have shown in the previous slide. So, it has got 1 ton or the ratio is 1 3 and 9, and subsequently what happened that thyristors, will be actually change.

So, with the previously introduce the ternary winding, the proportioned 1 is to 3 is to 9 a total of 27 steps is obtained only by 12 bi-sectional thyristor valve of different voltage ratings. So, this kind of configuration may solve, the previously discussed problem.

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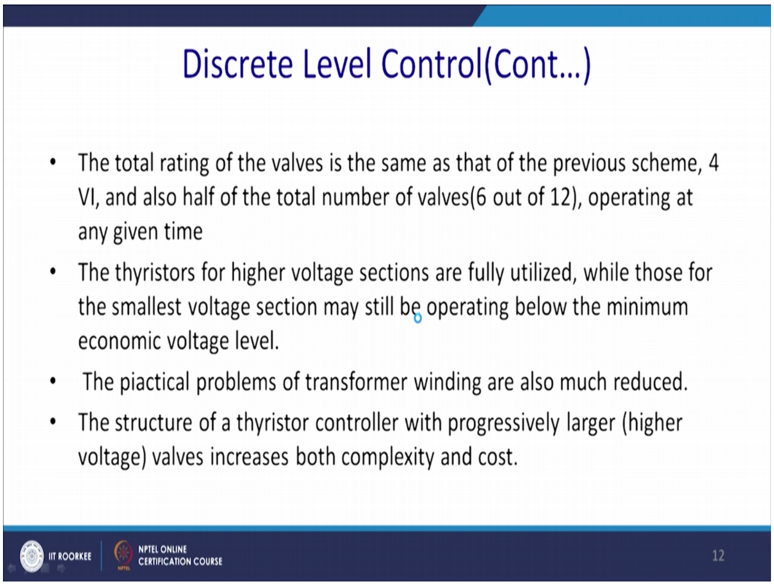

The total rating of the valve is a same as that of the previous scheme, 4 VI, and also the half of the total number of valves. So, 6 out of 12, is operating any given time that is reduces the conduction losses also. Thyristor of the higher voltage section are fully utilized, while those of the smallest sections of may still operating below the minimum economic voltage level.

The practical problem of the transformer winding are also reduced, because you do not need that much of the leads to be come out from your core. The structure of the thyristor control with progressively large, higher voltage increases both complexity and the cost both.

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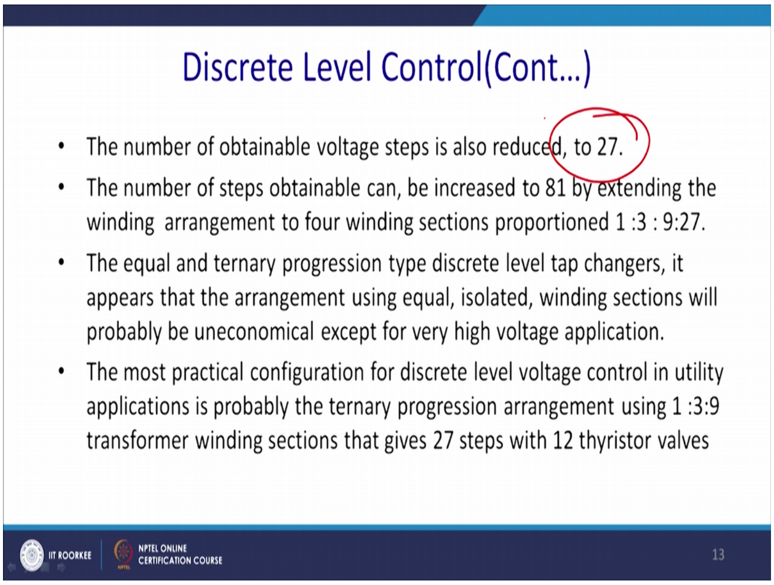

The number of obtainable voltage steps here also reduced, to 27, so that is something that we have to keep in mind. The number of steps obtainable can, be increase to 81, so we have to make another section to 27 that is all, so 1 is to 3, 9, 27; By extending, the winding arrangement for the four winding section proportional to 1, 3, 9, 27.

The equal and the ternary progression type discrete level tap changers, it appears that the arrangement using equal, isolated, winding section probably be uneconomical except for a very high voltage application. So, previous this kind of actually splitting is been preferred. Most practical configuration for the discrete level voltage control utility application is probably the ternary progression arrangement using 1, 3, 9 something like that transformer winding section that gives you 27 steps with 12 thyristors valve that is one of the biggest advantage of the discrete level control.

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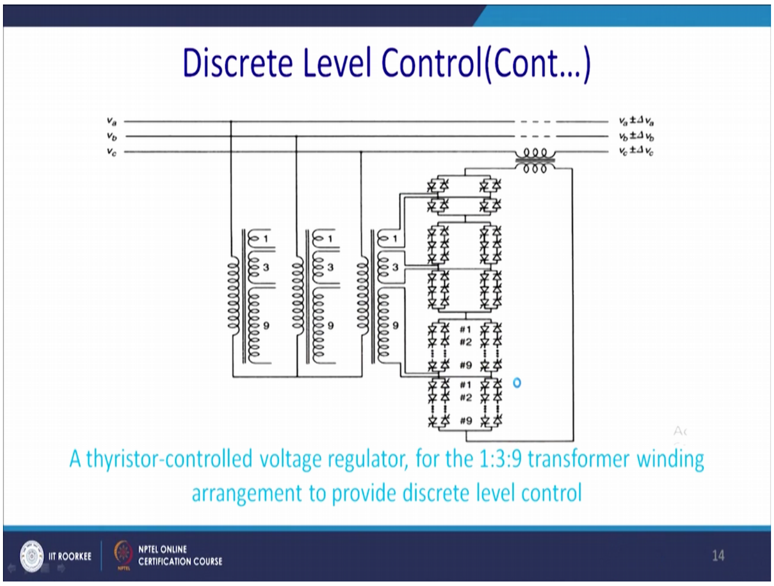

So, this is the case here. So, actually total circuit is shown in the phase 3. So, we can inject different kind of voltage in phase with del V, so that can be this, that can be this, or that can be this. So, this is the beauty of the discrete level transformer with 27 steps. The thyristor-controlled voltage regulator with 1, 3, and 9 transformer winding arrangement provides 27 discrete level steps.

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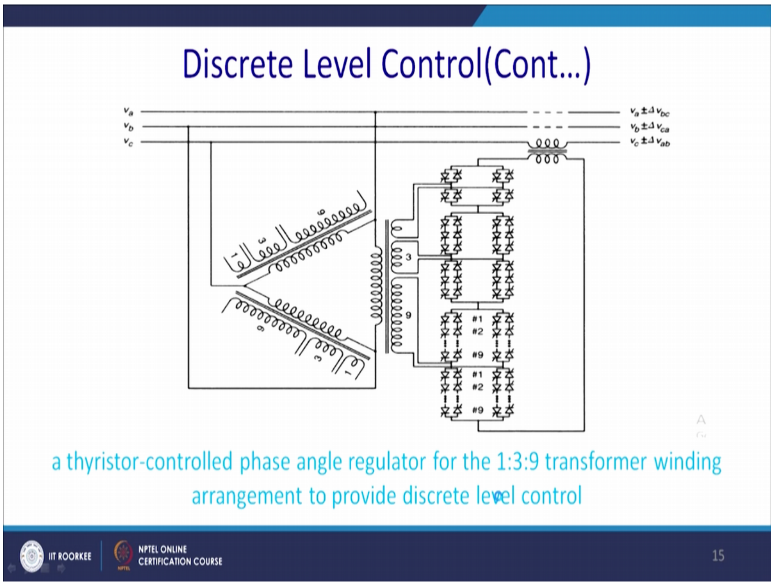

Similarly, the thyristor control phase angle, why we have to inject the voltage in quadrature. So, we can we have already seen that you know, if you want to inject in 90 degree with a phase a, we have to apply the voltage b c. So, thus this kind arrangement gives you the quadrature phase angle in only one phase has been shown.

So, this is with the a, and this is with the b, and the c. So, you know the delta, it will gives you 30 degree phase shift. A particular vector group is to be chosen, it is basically d 1 delta star 11 or 1. So, in this configuration, we can have a same thing and where voltage will be added with the quadrature that is b c, c a, and a b with the phase voltage that is will be the port, and that will be the actually the phase angle regulation. You inject the voltage in quadrature; the thyristor-controlled phase angle regulator for 1, 3, 9 transformer winding arrangement to provide discrete level control.

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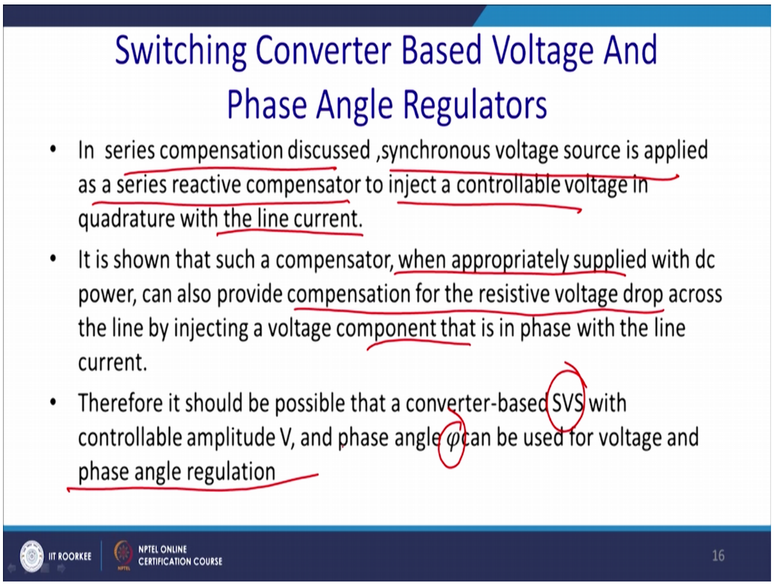

So, a switching converter based voltage and the phase angle regulator, let us have a comparison between these two. Series compensation discussed, synchronous voltage sources applied as a series reactive compensator to inject the controllable voltage in quadrature with the current. So, this is the principle of operation.

It is shown that such compensator, when appropriately applied supplied with the dc source or dc power, can also provide compensation for the resistive drop across the line by injecting the component that is in phase with the current. Therefore, it should be possible that a converter-based SVS with controllable amplitude V, and the phase angle phi can be used for voltage and the phase angle regulation. So, it can control both. So, this is the converter-based regulator.

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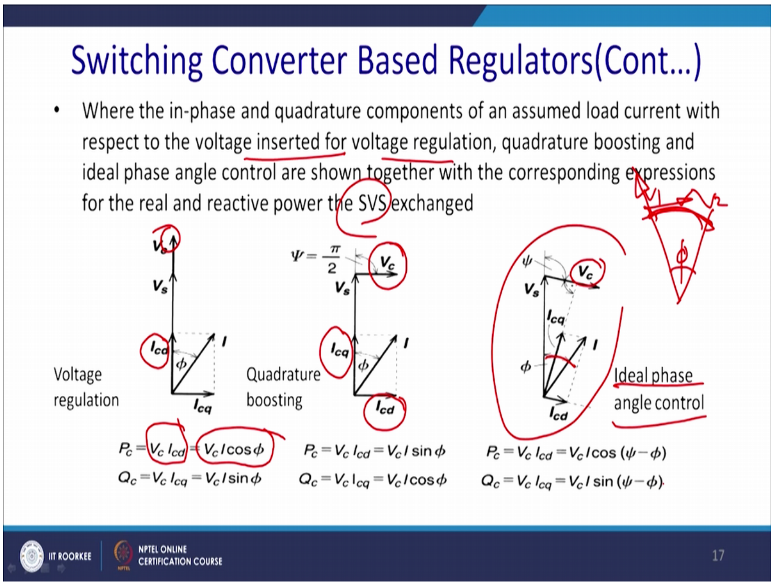

Where in-phase and the quadrature component of an assumed load current with respect to the voltage inserted in voltage regulation, quadrature boosting that we have discussed in previous class, and ideal phase angle control are shown together with corresponding expressions of the real and the reactive current and the power exchange by SVS. So, this is basically the supply voltage, and this is the interest component, and this is high and you add up by c. So, this is essentially the voltage regulation what happened then, since you have applied a real current, and then voltage.

So, what happened actually V c into I c d, so ultimately the that particular component of the power will be I c V cos phi. Similarly, I c q sin phi will be the Q c, and this is for the voltage regulation. Same way, we have a quadrature boosting you have you inject actually the current perpendicular to the V s. So, what happened then, actually c d will come in this way, and i q will be coming this way.

And thus that actually new P c compositing power, real power will P c into I c d that will be I in sin phi, and similarly it will be cos phi. But, in real angle control you know, there what you can do, you can inject basically V c with any angle phi. And in that way, you can also compensate real power as well as the active power.

So, this is the ideal phase angle control, because you have to inject current into arc. So, this one is V 1, this one is V 2, and this one is actually phi. So, you have to inject in this way, not in this quadrature or in-phase. So, how can you inject in a arc, this can be this is ideal phase angle regulator, where actually you have to find it out this phi, and from their actual there is will be a calculations of shy.

So, form there you actually inject is voltage as regulated by this particular power angle regulator, not exactly at phase, not exactly at quadrature. So, then expressions becomes, in this case from this phasor it is V c into I c d should be the real power. So, it is V c I cos shy minus phi that should be the angle and Q c will be P c I q c should be you see I sin phi minus psi minus phi.

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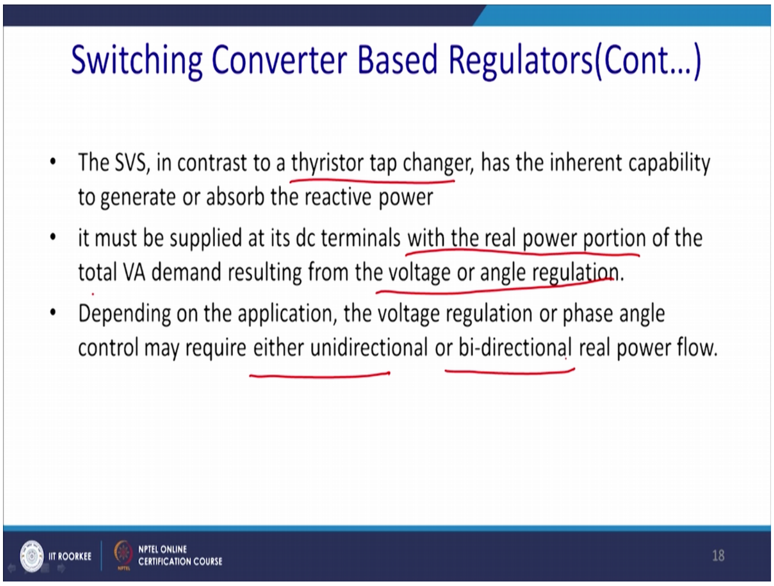

Now, switching off the converter based on the SVS. What is the actually difference between the discrete component based thyristor. SVS, in contrast to the thyristors tap changers, has the inherent capability to generate or absorb the reactive power, this is one of the biggest advantage of it.

It must be supplied, and it is and dc terminal with the real power that is one of the requirement you required to a power source. Real power portion of the VA demand resulting from the voltage or angle regulation. Depending on the applications, voltage regulation or the phase angle control may require either unidirectional or bi-directional flow of the real power. So, that is something we required to keep in mind, while designing that SVS base P r.

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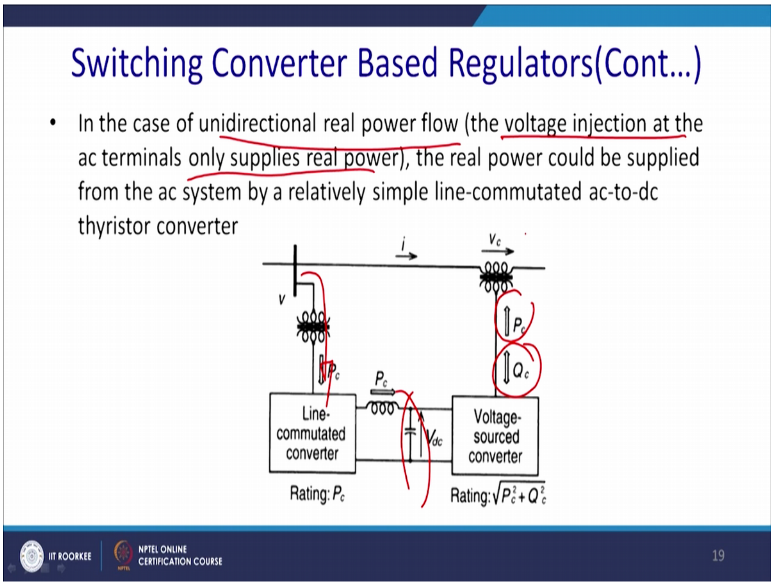

So, this is the case of SVS base P r. So, this is a switching converter based regulator. In case of the unidirectional real power flow, the voltage injection at the, terminal voltage injection at the ac terminal only supplies the real power. The real power could be supplied from the ac by a simply a line commutated ac-to-dc thyristor converter. So, thus in this way, the real power will go, and this will maintain the dc bus voltage, and from there this is a voltage source converter, this will compensate the requirement of this Q c and the P c as result.

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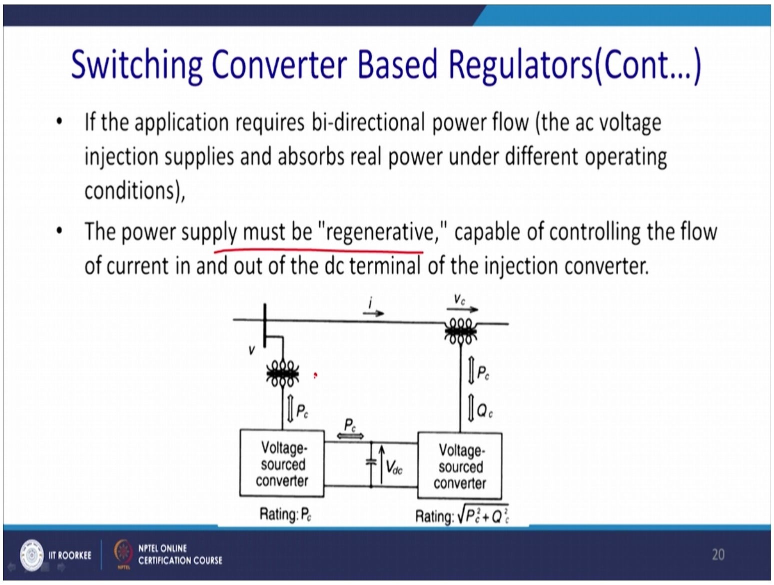

So, if the application required the bi-directional flow bi-directional power flow, the ac voltage injection supplied or absorbed, the real power under the different operating condition. Then power supply should be regenerative, capable of controlling flow of the current and out of the dc terminal of the injection converter. So, power has to be bi-directional.

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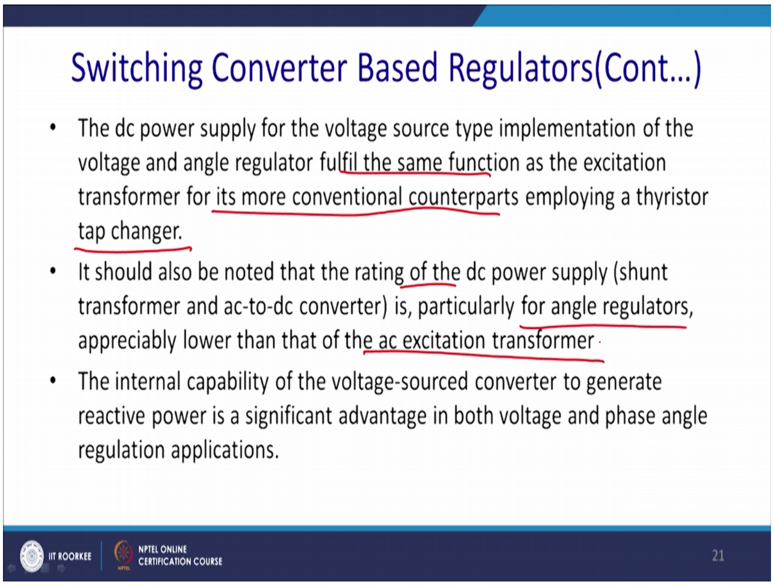

So, in this case, we have to change some kind of topological aspect. So, what happened, the dc power supply for the voltage source type implementation of the voltage and the angle regulator fulfill same function as the excitation transformer for its more conventional counterparts employing a thyristor tap changer.

It should be noted that the rating of the dc power supply, and the shunt and ac-to-dc converter is, particularly for a angle regulators. Appreciably lower than that of the ac excitation transformer. The internal capability of the voltage-sourced converter to generate, the reactive power is significant advantage of both voltage and the phase angle applications.

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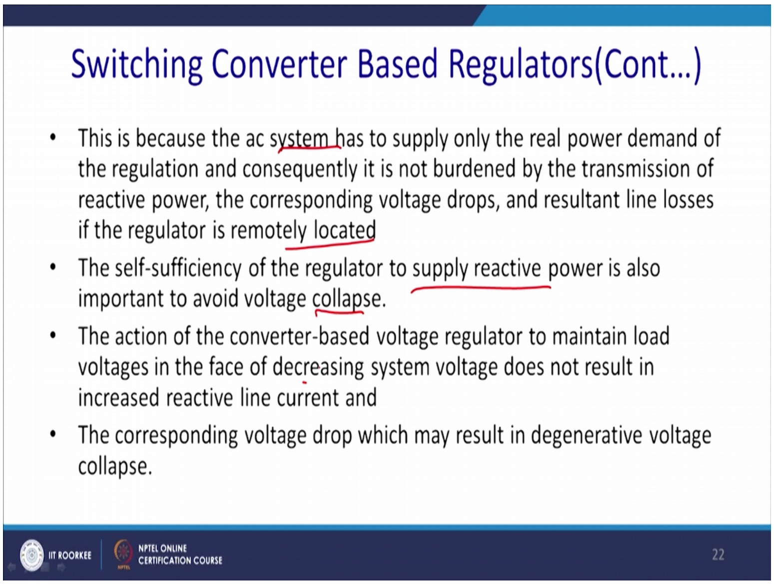

This is because the system has to supply only the real power demand of the regulations, and consequently it is not burdened by the transmission of the reactive power. The corresponding voltage drops, thus what happened, and result in the line loss give the regulator is remotely located, this is actually one of the drawback. The self-sufficient sufficiency of the regulator to supply the reactive power is also important to avoid voltage collapse. That is something it has a self-healing mechanism.

The action of the converter-based voltage regulator to maintain the load voltage, in the phase of the decreasing system voltage does not result in increase reactive line current. The corresponding voltage drop, which may result in degenerative voltage collapse that is something we required to take care of it.

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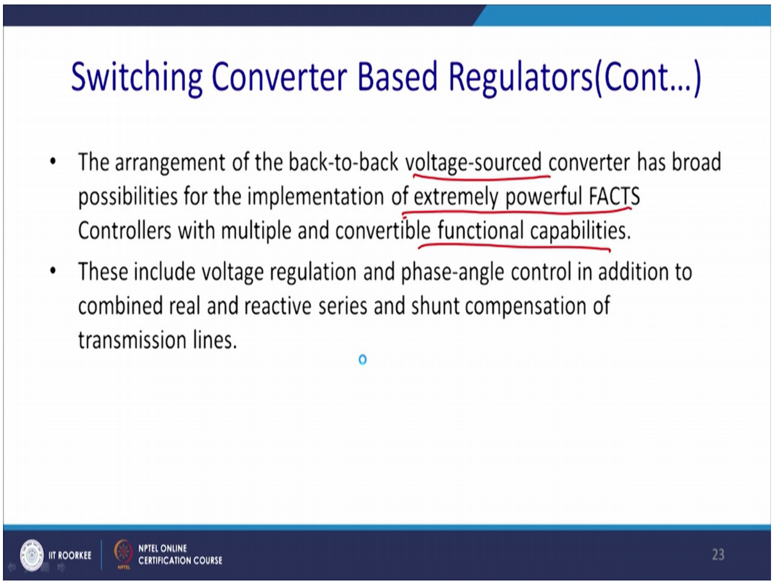

So, for the session the arrangement of the back-to-back voltage-sourced converter has broad possibilities of implementation of the extremely powerful FACTS controller, which multiply with multiple convertible functional capabilities. And what happened you know, here this converter essentially will hold this dc link voltage. And thus, the another converter in right hand side, can do work very well, and these include the voltage regulations, phase-angle control in addition to the combined real and the reactive power, and series compensation of the transmission line.

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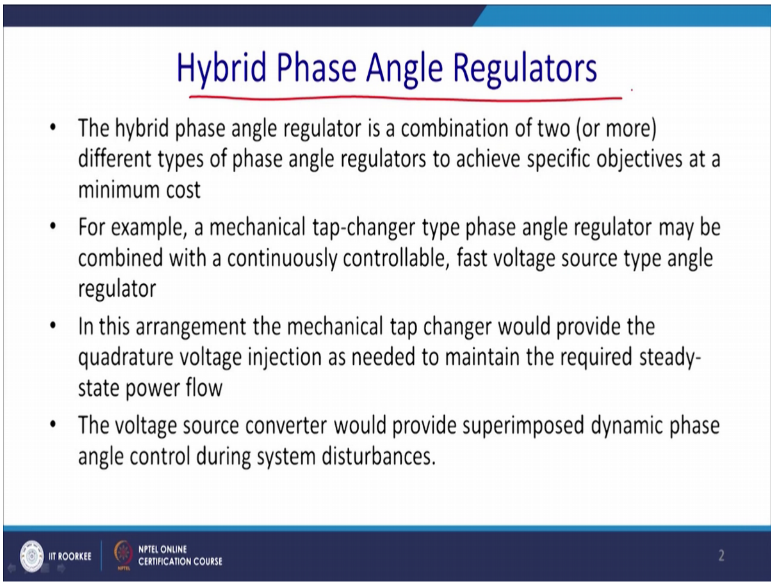

So, phase angle regulator, this is called hybrid phase angle regulator. We have seen that you know, most of the cases, the voltage injected in quadrature to shift the change, then can we do something. So, that you know, we can inject in any phases, and optimal compensation can be achieved. In that case, we consider a hybrid phase angle regulator. Hybrid phase angle regulator, it is a combination of may be the one, it is injecting in phase, another you injecting in quadrature or any other angle; Two or more different type of phase angle regulator to achieve the specific objective at minimum cost.

For example, a mechanical tap changer type phase angle regulator may be combined continuous combined with the continuously controllable, fast voltage source type angle change regulator. There we can use a phase factor, so that will be actually very correctly calculate that magnitude of the voltage and phase require and inject that. So, this is the actually the mechanical version of it will be actually the mechanical tap changer type phase angle regulator.

In this arrangement, the mechanical tap changer would provide the quadrature voltage injection, we know that if you wish to inject quadrature with phase a, we required to inject b c needed a maintain the required the steady state power flow. The voltage source converter of instead of the mechanical switch devices, would provide superimpose dynamic phase angle controlled during the disturbances, and thus it is preferred.

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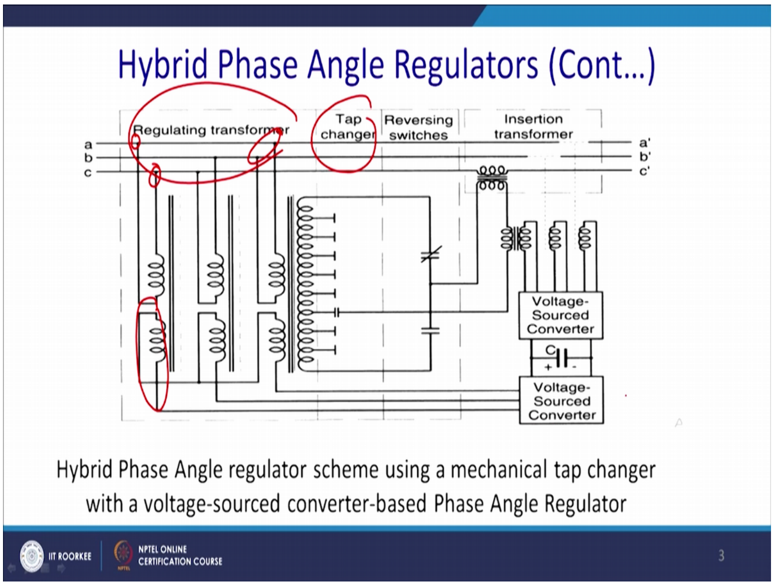

So, see that you know, this is actually the regulating transformer. And these are the tap changer. And the reversing switches, and it is a insertion transform. So, you got a different phases, for example, this is a b c. So, these and these is a c and this will is be sensed and similarly a c a b b c, c a. And accordingly, these are the taps, so we can change the number of taps as an where it is required. So, based on that for example, you know this is the a b phase, and so it will be linked with some voltage of a b to compensate the voltage in this phase c.

Similarly, you have a voltage source converter, which exactly actually calculate the amount of the voltage require. So, you may require to compensate let us say 35 degree, then some portion will be quadrature, and some portion will be your actually in phase, instead of applying in quadrature and phase. These are the property you know, if it is a phase vector, it can inject in the phase types of the two level inverter of 60 degree.

So, you can make, the combination of the voltage that is 65 degree you required to inject that can be that can come from the quadrature, as well as by this. So, these two voltage will be added in series, and will give you the these are voltage. And this converter x very fast for this reason, the compensation will be very accurate.

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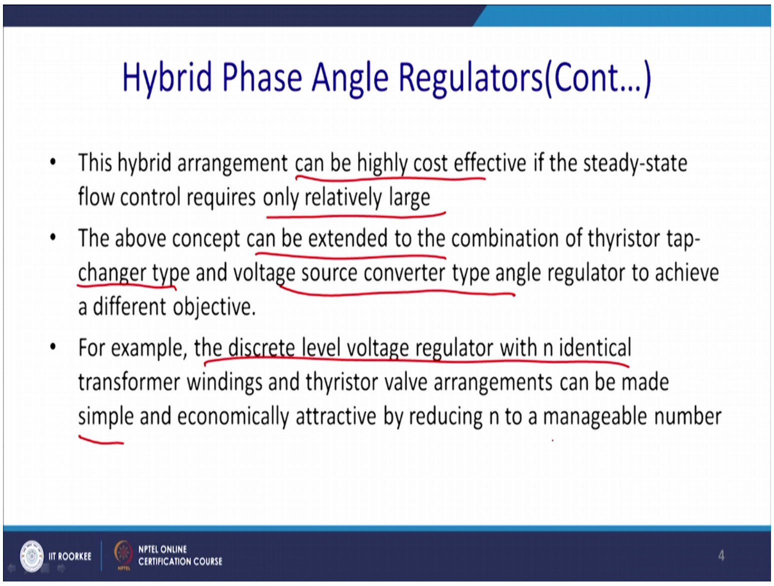

So, what are the advantages of this hybrid phase angle regulator. This hybrid phase angle regulator can be highly cost effective. (Refer Time: 31:46) one part is actually mechanical, and thus you compensate the bulk power and the power handling capability of this of this part of the converter actually voltage source inverter, can be of the low rating low power rating. And thus you can actually reduce the cost of the component. If the steady state flow power control require only the reactive, only the relatively large form. So, you require only inject the quadrature power. So, transformer itself will be sufficient to do that.

The above concept can be extended to the combination of the thyristor tap changer type, voltage source converter type. The thyristor and the voltage source converter type angle regulator to achieve different objective. Different objective means, you required to inject the particular voltage and the phase. So, that can also be achieved by this hybrid phase angle regulator.

For example, the discrete level voltage regulator with an n identical transformer winding, and thyristor valve arrangement can be made a simple economically attractive, it reducing the n manageable number. For this is we can student may actually refer to the contrast, this kind of transformer is called sense transformer, is one of the versatile phase angle regulator. We shall give it to this sense transformer in the reference.

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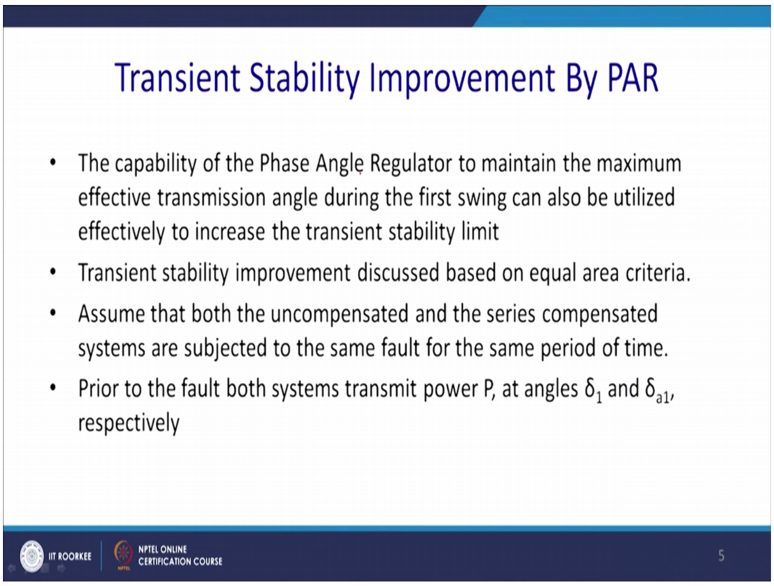

Now, let us discuss about the enhancement of the transients by phase angle regulator. So, the capability of the phase angle regulator, to maintain the maximum effective transmission angle during the first swing, can also be utilize effectively to increase the transient stability limit. So, by changing delta, it enhances the power handling capability, and thus in the first swing, it can increase the power flow through this transmission network.

Transient stability improvement discussed, we will be again take on the equal area criteria. And we will be show that how the transient stability is enhanced by the presence of PAR. And let us take the same equal area criteria, and assume that both the uncompensated, and the series compensated systems are subjected to the same fault for the same period of time; Prior to the fault, both system transient power, at an angle delta 1, and delta 2 respectively.

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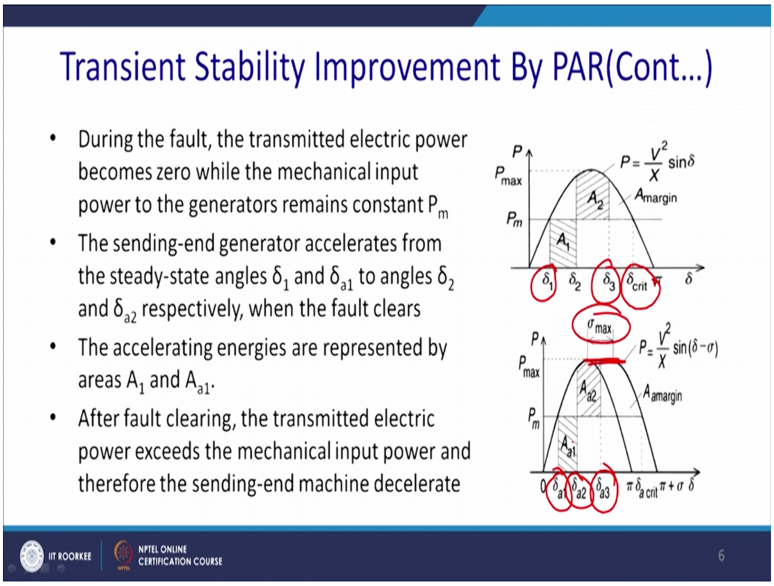

Let us referred to the figure so, you know, this is the this is the equal area criteria and uncompensated one. Delta 1 was the was the delay angle, and then you got a accelerating area A 1, and ultimately due to that you know, you got other deceleration area A 2. And a and you know that actually fault required to be cleared. And let us assume that fault been cleared at del del 3 and how was this critical fault clearing angle is delta critical.

On the other hand, you know with the PAR, let us assume that it is the same delta 1, we shall market as a delta A 1, and the exhilarating area is actually change to delta A 2. But, here you know, you have a range you have actually change to the value, and you can add sigma may be 45 degree, in this direction as well as this direction.

Thus you know, the maximum power handling capability P max will vary with the huge amount of range. And thus what happened, even though you actually clear out the fault, and delta A 3 you have delta critical is been shifted by shifted by this angle, that is pi plus sigma. So, your so this actually breakers another system, what enhance time to actually mitigate the fault as well as enhances the transient stability.

So, let us take one by one. During the fault, the transmitted electric power becomes zero, and thus it is a cost of the accelerating area. While the mechanical input power to generate it remains the P constant, that is P m. So, this is given by this value. The sending-end generator thus accelerates from the steady-state value delta 1, and delta a 1, in case of the presence of the PAR to delta 2 to delta a 2 respectively, and when fault is cleared.

The accelerating result energies are represented by A 1 and A a 1. So, both area are essentially same, there is no difference. After fault what happen, after clearing the fault, the transmitted electric power exceeds the mechanical power. And therefore, sending-end machine decelerates, and this is basically the deceleration area.

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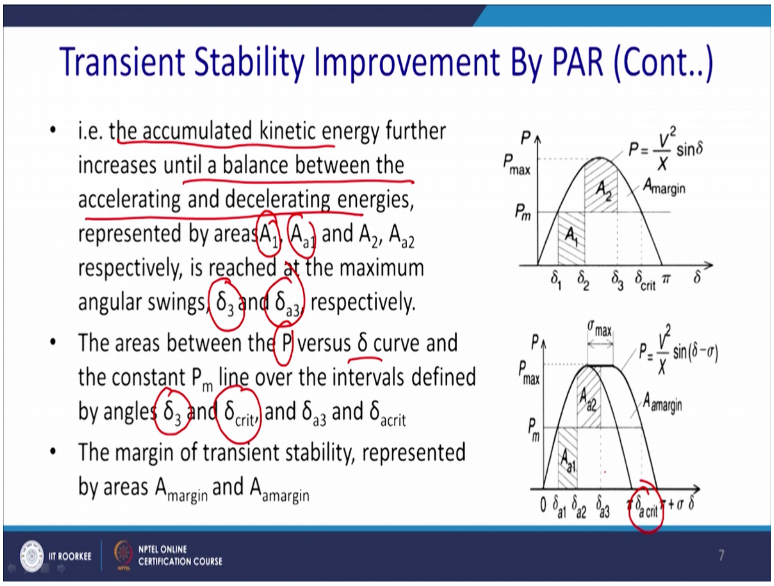

That mean, the accumulated kinetic energy further increases, until the balance between the accelerating and the decelerating energies are established. Energies, and it represented by A 1, and A 1 and A 2, and A 2 respectively, is reached at the maximum angle of swings delta 3 and delta a 3, respectively.

The constant between the areas between the P versus delta curve, and the constant P m line over the interval is defined as delta 3, and delta critical, and delta a 3, and delta a critical. So, this is actually delta a critical. The margin of transient stability is represented by the area, A margin and A a margin. So, this is basically the A margin. So, this is basically A margin, you can see that this is the limit of the stability. And here, this big area is A a margin, which is actually quite enhanced.

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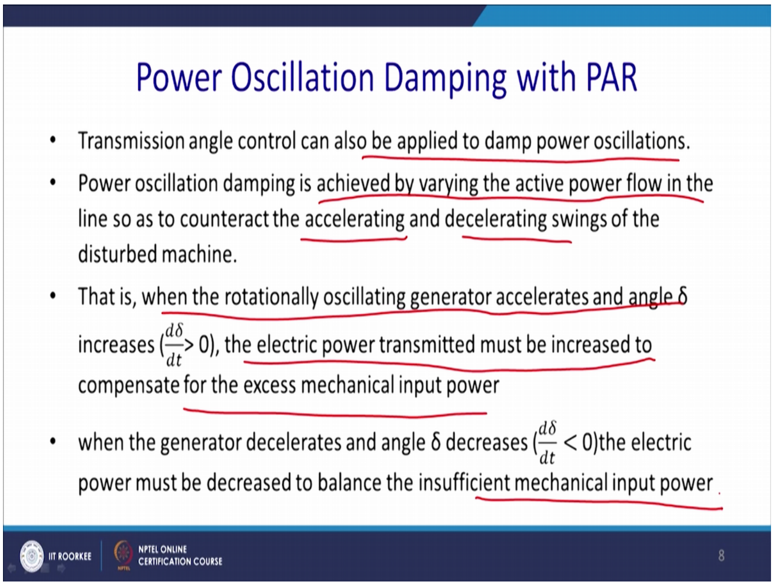

Thus similarly, it can mitigate the oscillation. Transmission line power can also be applied to damp the power oscillation. We have seen in case of the series, against of the shunt, and it is also applicable for the power angle regulator. The power oscillation damping is achieved by varying the active power flow in the line. So, to counteract accelerating and the decelerating swing of the disturb machines on line.

That is what happened, when the rotationally oscillating generator accelerates at an angle delta increases, then del s del delta by del t, should be greater than 0 that will be (Refer Time: 39:53) and acceleration sorry. The electric power transmitted must be increased to accommodate the enhanced extra power, to compensate the excess mechanical power. When generated decelerates, the angle decreases and the electric power must be decreased to balance the insufficient mechanical input power.

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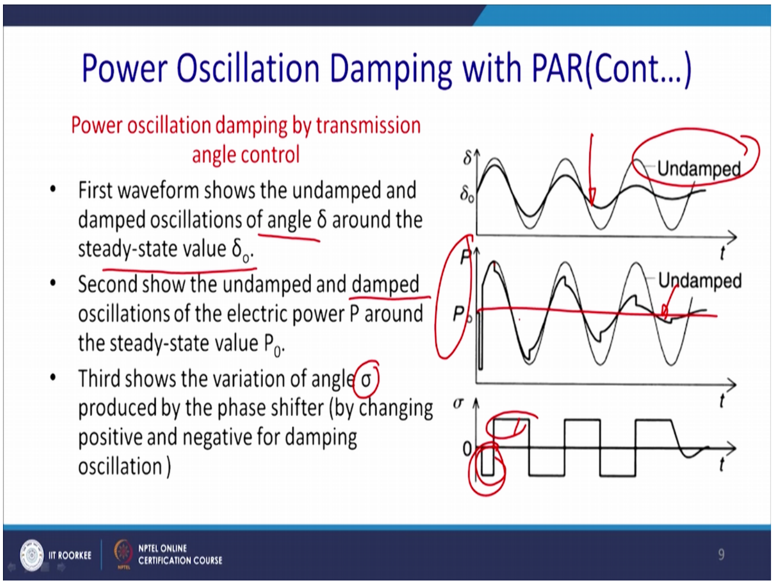

So, this is the case. Now, this is basically the uncompensated delta. And with this damping ultimately this way from become this, this is the compensator delta. First waveform shows the undamped, and the damped oscillation of angle delta around the steady-state value delta 0.

The second shows, the damped and undamped oscillation of the electrical power, since it is oscillating. So, electrical power also will have a main dc that is P 0 over it, it will oscillate, and quiet dangerous. Oscillation of the electric power P, around the steady-state value P 0; so, this one is undamped, and when it is being damped you will have this kind of features.

The third shows, the variation of angle del sigma produced by the phase shifter, gradually what you will do you will actually. Change the phase of it generally, it is started a quadrature and accordingly will change. And generally, what you can see that. So, since it is actually positive, so you inject the negative phase, so bring it down. And you inject the positive phase to actually bring it down, the negative change in delta.

So, by phase shifter by changing the positive and the negative damping oscillation, you gradually actually by changing sigma, you gradually bring down the delay angle to this steady-state value. So, thus this can deliver damp power effectively the power oscillation.

Thank you for your attention. This thus we conclude our discussions of our third topic that is the voltage and phase angle regulator. We shall now, we shall continue now, the next topic that is on UPFC and UPQC, while series, and shunt, and the PAR been combined into the single entity. And for this session term universal or unified is added. We shall continue to our discussions.

Thank you for your attention.